IV Conferencia Panamericana de END
Buenos Aires – Octubre 2007

AAENDE
Asociación Argentina de Ensayos No Destructivos y Estructurales

The application of radiometric method for quality assessment of linear accelerator shielding structures

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Abstract

The development of the modern technical society is linked to the use of ionizing radiation sources. In addition to nuclear power plants, there are the other significant ionizing radiation sources, for example, linear accelerators which are used both in radiography and in oncological therapy. The conditions for ionizing radiation source management become more and more stricter, and hence the higher demands are stipulated for the supervision of shielding structures of linear accelerators during their construction. The radiation density gauge for fast and flexible controls of the densities of fresh concrete mixtures has been successfully developed at the Faculty of Civil Engineering, Brno University of Technology.
It is the radiation density gauge which revealed a serious failure during routine inspections of shielding concretes at a linear accelerator in the Brno Hospital. It was found that the density of heavy-weight concrete did not reach the prescribed calculated value. This failure was caused by a reduction of the density of heavy-weight aggregates used for production of heavy-weight concrete while it was not possible to remove this failure flexibly during construction. Hence, the placing of concrete was completed with the reduced density, and based upon the results of radiometric density measurements it was recommended to build an additional structure shield with different thick steel sheets. The final measurements of the regulatory body have proved that the additional shield was designed correctly.

1. Introduction

Ionizing radiation, among other mostly used in industry and medicine, is also the significant factor that affects adversely the environment. The old and less powerful gamma sources and betatrons are gradually replaced by linear accelerators that are ranked among the most powerful sources (with the exception of nuclear power plants).
Linear accelerators are irreplaceable both in industry, where they are used in weld testing and thick cast testing, and in medicine for cancer therapy. The environment is protected against the harmful effects of ionizing radiation by robust reinforced concrete constructions with precisely calculated wall thicknesses (Fig. 1).

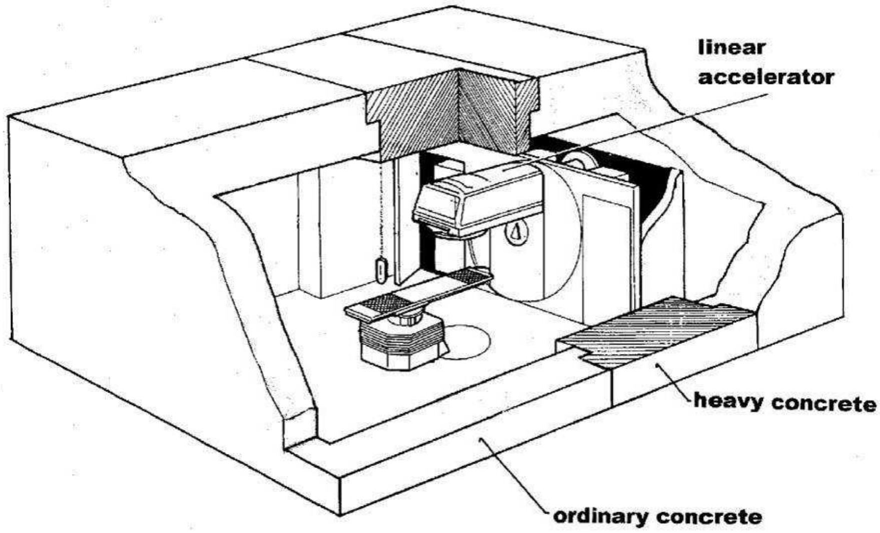

Figure 1. A typical concrete enclosure that shields the linear accelerator

From the economic point of view, it is advisable to use ordinary concrete for the shielding constructions. Only in the case that ordinary concrete does not provide the sufficient protection taking into account the dose rates and the arrangement limitation of the external area, heavy-weight concrete for the shielding construction can be applied.
When the concrete shielding constructions are designed, the priority is to achieve the highest density, preferably without any special aggregates with higher densities (e.g. baryte, iron ores, etc.) and cast-iron gravel. The special attention must be paid to avoid creating local cavities, non-homogeneous clusters, undesired porosity and other defects. All such defects in wall and ceiling constructions at the workplaces with ionizing radiation sources would exhibit a remarkable deterioration of the environmental radiation protection. Their additional removal is extremely difficult, and hence it is necessary to check continuously the prescribed composition of concrete mixture and to supervise if the required technological procedures are observed, especially during the placing of concrete and the consolidation of concrete mixtures(1).
The VUT XI radiation density gauge which was developed at the Faculty of Civil Engineering, Brno University of Technology is very helpful during the continuous control of the densities in robust shielding constructions.

2. General development and application of radiation density gauges

Radiation density gauges were developed in the 1960s, at the beginning of nuclear power engineering epoch. Their main purpose was to secure immediate measurements of the densities of fresh concrete mixtures from which the shielding constructions of nuclear reactors and other ionizing radiation sources were built.
Afterwards, the radiation density gauges were also used in other branches, for example, for earth, sand and gravel consolidation of rockfill dams. They can be also used in road and highway constructions for subsoil and embankment consolidation (in case of gravel

and crusher-run material, the application of radiation density gauges is somewhere the only precise control method) as well as the final layer consolidation. Radiation density gauges are successfully applied in railway constructions to control the efficiency of building machines applied for gravel ballast under rails. They are also applied for vault construction in banks where a small variation of concrete density must be avoided to achieve the vault safety.
As compared with other density measuring methods used for building materials, the radiometric method has two great advantages, the first one based upon fast measurement of a huge volume of the material tested and the second one that the density and/or the consolidation are determined immediately. Hence these parameters can be continuously controlled. In case of non-conformity between the measured and required value, the countermeasures can be realized immediately and relatively cheap. Additional repairs are usually demanding and very expensive. The impact of radiation density gauge application in situ to work attitude should be also considered. Poor quality work is revealed immediately. Its application compels the workers to better discipline and high quality work.

2.1 Principle of radiometric measurement

The radiometric density measurement is based upon the principle of gamma radiation attenuation and gamma radiation scattering in the measured material. The sources of ^{137}Cs and ^{60}Co are very often used for such measurements. To detect gamma radiation, GM tubes, scintillation detectors and semiconductor detectors which are connected to the processing unit are very often applied. Counts per second (cps) are detected which must be converted by means the calibration curves to the density. The sophisticated measuring instruments have built-in the calibration curve in its processing unit in the software application and the results on the screen are presented in kilograms per cubic metre. The accuracy of measurements is stipulated in the standard and it is ± 20 kg.m^{-3} for the complete range of the densities. To achieve such accuracy, it is necessary to count in the processing unit more than 10,000 counts within 3 minutes. The geometric arrangement of the radiometric units and the source activity must also comply with this requirement. From the constructional point of view, the source is stored during transport in the shield from which it moves to the operating position at the site of measurement. When the method of attenuated gamma radiation detection is applied, the source and the detector are placed in the opposite positions of the tested sample. The density between the detector and the source is determined based upon the measurement. This method gives very precise results. If the material with a superficial mass $\rho_A \leq 400$ kg.m^{-2} is to be measured, it is recommended using ^{137}Cs. The prerequisite is to maintain the stable geometric arrangement of source – detector.
In case of the stabbing radiometric sets used for controls of the density of fresh concrete mixtures when the source is assembled in the casing and stabbed into the material or inserted into the bore-hole, the detector is installed outside the material tested (Fig. 2).

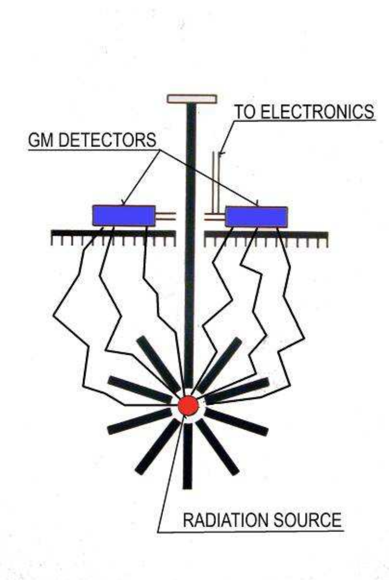

Figure 2. The radiation density gauge - scheme

For attenuation of gamma radiation, the modified formula for broad beam is applied:

$$N = B.N_0.e^{-\mu_m \cdot \rho_A} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where
N - is the count rate of attenuated gamma radiation [s^{-1}]
N_0 - count rate of original beam [s^{-1}]
B - build-up factor [1]
e - natural logarithm base [1]
μ_m - mass attenuation coefficient [$m^2\ kg^{-1}$]
ρ_A - superficial mass of material [$kg\ m^{-2}$]

The superficial mass of the material can be calculated from the following formula:

$$\rho_A = \frac{1}{\mu_m}.\ln\frac{B.N_0}{N} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

The density of the material tested is given by the following formula:

$$\rho = \frac{\rho_A}{d} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

ρ - is the density [$kg\ m^{-3}$]
d - material thickness [m]

The detection units measure the average density in the layer between the source and the detector. The stab depth ranges from 0.05 to 0.4 m.

2.2 Constructional design of VUT XI radiation density gauge

Based upon laboratory tests and experience from the production of many prototypes, the radiation density gauges using the stabbing principle have been developed at the Faculty of Civil Engineering, Brno University of Technology. Based upon the „in-situ“ measurement experience, the radiation density gauges are innovated and updated. This innovation is aimed at reducing total weight of the gauge and improving the operator comfort during operation. The former shielding material (i.e. lead Pb with the density of ρ = 11,360 kg m^{-3}) has been replaced with depleted uranium ^{238}U (ρ = 19,200 kg/m^3). This shielding material is relatively cheap and easily available because it is generated as waste during the fuel production for nuclear reactors. With the same shielding effect, the weight of uranium amounts to about one fourth of lead weight (i.e. 0.75 kg of uranium compared to 3 kg of lead). The weight of radiation density gauges has been reduced from the original 13.5 kg to 5 kg. Also the detectors have been innovated. The original GM-tubes were replaced by the most sophisticated semiconductor detectors. The semiconductor detectors used in the radiation density gauges are unique in the Czech Republic. They operate under normal operating temperatures and their sensitivities are comparable with those of GM-tubes. Their advantage compared to GM-tubes is a longer life and a shorter dead time which extends the measuring range towards the lower densities for the source used and for the stab depth of about 10 to 15 cm.

The VUT XI radiation density gauge consists of two parts which are connected each other with a duralumin tube (Fig. 3). In the lower part, the shield with the source, rechargeable batteries and detectors are installed. In the upper part, the processing electronic unit and the front control panel with all control and communication elements are installed. This arrangement complies with the ergonomic requirements because when you handle the gauge and you read the data on the display it is not necessary to bend to the radiation density gauge. The radiation density gauge is provided with replaceable castings and it is able to measure in the following depths: 0 (surface geometry), 10, 15, 20 and 25 cm.

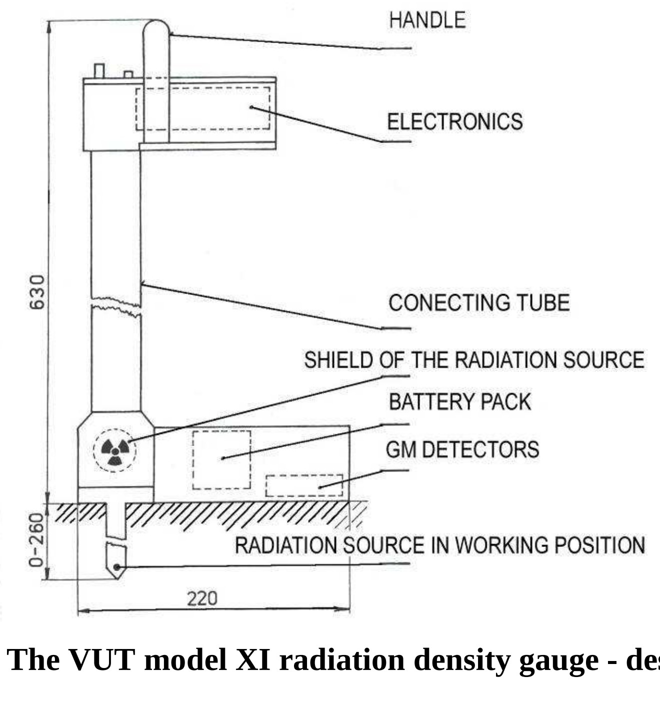

Figure 3. The VUT model XI radiation density gauge - description

A microprocessor-controlled processing unit (assembled from the components and using surface assembly technology) is the basic part of electronics in the gauge. The software used is user-friendly and it provides high user's comfort. Up to 900 data of the densities measured (including the measurement depth and the measuring time) is stored into the internal memory of the radiation density gauge for the later application and transfer to a host PC for the data processing. The operator is informed by the acoustic signal that the measurement is completed, the radiation danger is present or the source is not place in its position in the shield and/or inserted into the material measured. The test program controls the proper operation of the gauge; additionally it informs the operator about 2 hours before the batteries are discharged.

2.3 Practical application of the radiation density gauges

The density of fresh concrete mixtures is usually tested in two following phases:
a) Concrete mixture is tested in a test vessel of each mixer truck (Fig. 4)
b) Placed and processed concrete mixture is tested directly at the site in formwork (Fig. 5)

Figure 4. The concrete mixture testing before placing to formwork

Figure 5. The concrete mixture testing in formwork

Unequal properties of individual components in the concrete mixture, non-uniformity of production and composition of the concrete mixture as well as transportation, placing and consolidation can deteriorate the concrete quality and the shielding effect, especially if some mentioned effects occur at the same time. The purpose of testing is to continuously monitor consolidation of the concrete mixture and, if necessary, to carry out the countermeasures. Hence the radiometric density test using the radiation density gauge is performed immediately after the placing of concrete mixture and its consolidation.
The casing of the radiometric density gauge must be fully pushed into fresh concrete so that the lower part of the gauge with the detectors is positioned on concrete and no air

gap is formed between the tested material and the detectors. The casing must be pushed into the material in the vertical direction. Subsequently, the source is released towards the operating position and the measurement starts (Fig. 5). The gamma radiation impacted on the detectors is converted into electrical pulses which are processed in the processing unit and displayed on the gauge screen as the density data [in kg.m^{-3}].
In case that the average density at the site of measurement would be lower than the required density, the site must be reconsolidated by immerse vibrators, or other countermeasures must be immediately performed to improve the concrete quality. Subsequently, the test at this site is repeated.
If the steps described above are carried out, the density better than expected in the project shall be achieved.
Densities of the concrete mixture which are measured in the test vessel and in formwork during the placing of concrete are recorded directly at the site in the prepared ground plan building layouts (Fig. 6). These records are used for the radiometric test post-assessment at the Brno University of Technology workplace(2).

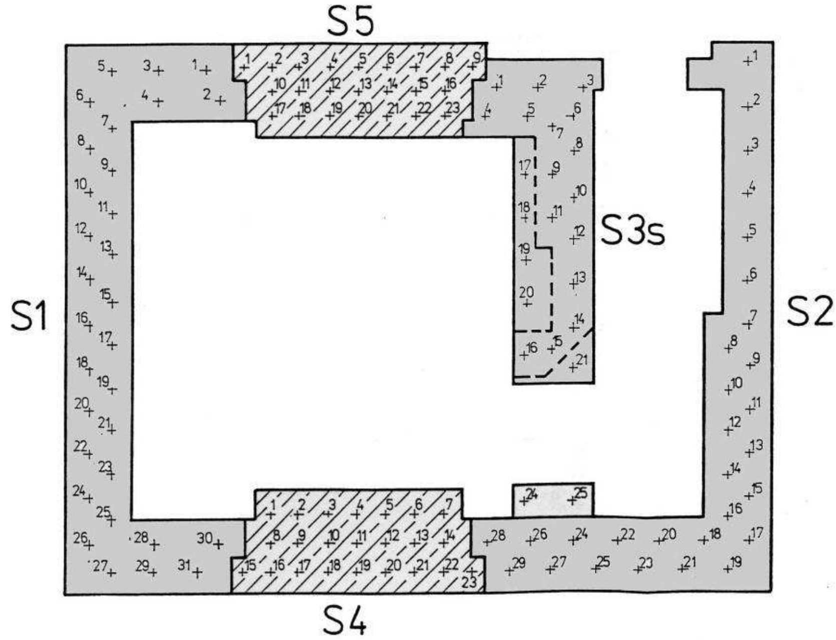

Figure 6. Example of record in the building ground plan

As an example, we can present in this paper the density testing of the placed concrete mixture at the building site of the biological shielding of the radiotherapeutic building which was constructed on the hospital grounds in Nový Jičín. In total, 238 mixer trucks and 1,003 test points in walls and ceilings were measured.
The results were processed on a PC. The program used was based upon the Gaussian distribution. The complete set of results was statistically tested for individual layers, walls and ceilings. The calculated data was clearly arranged in tables. From the data calculated, the Gaussian distribution coordinates were calculated, for example, inclination, sharpness, and the coordinates of inflex points.
Based upon knowledge of the average density ρ_0 and the standard deviation **s,** the shielding concrete density can be determined ρ_g. This density is equal to the average density ρ_0 reduced by the factor of 1.64 multiplied by the standard deviation **s**. The guaranteed density ρ_g, used as the input value during calculation and evaluation is the

density which is not achieved in 5 % cases of measurements at 95 % confidence interval (Fig. 7).

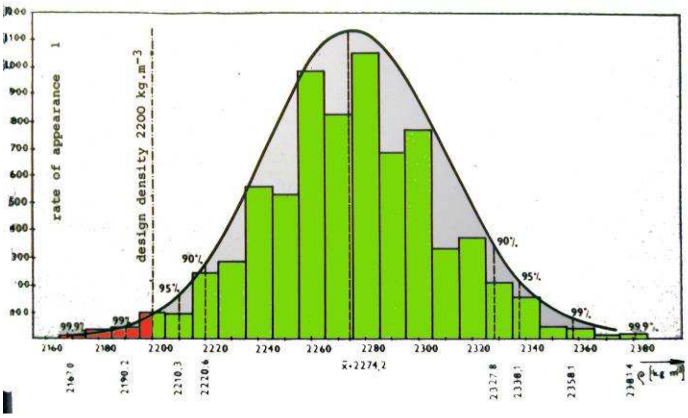

Figure 7. The statistical evaluation of concrete density

This value is critical in compliance with „The Statistical Methods for Concrete Assessment“ recommendation. Its value must not be lower than the designed minimum density. This requirement was fulfilled in the complete scope of the shielding concrete construction, for walls and ceilings.

3. Defects found in shielding constructions and their remedy

The most serious case when the density of concrete was not observed was recorded during the construction of linear accelerator at the Oncological Centre, Zluty kopec Hospital in Brno when the minimum density of ordinary concrete of 2,200 kg m^{-3} was prescribed and the minimum density of baryte concrete was 2,950 kg m^{-3}. According to the densities of calibration concrete samples (Fig. 8) made in the laboratory in compliance with the formula, it might be expected that the placing of concrete should be realized trouble-free.

Figure 8. The radiation density gauge calibration

However, it was found during continuous testing of the densities for „in situ“ concrete mixtures (Fig. 9) that the constructional shielding properties are unsatisfactory (more than 5 % of the data measured was below the minimum limit). This was caused due to a bad technical condition of the concrete mixing plant as well as due to non-observance of technological concrete production regulation. It was the serious defect and the situation had to be solved accordingly.

Figure 9. The concrete consolidation control during construction

To observe the master plan, the halt of construction as well as a change of the concrete mixing plant were not possible. A new minimum density of heavy-weight concrete was changed from the original 2,950 kg/m^3 to 2,700 kg/m^3 which was critical for concrete production as well as for the measurement; and the project was modified accordingly.

Figure 10. The additional steel shielding

The project modification was based upon an additional layer made of steel sheets which replaced a reduced superficial mass of walls and which was fixed to the construction after completing the placing of concrete and a removal of formwork (Fig. 10).
The composition and the thicknesses of new shielding constructions were recalculated according to the new minimum values of the densities in the modified project so that the original shielding effects of particular walls and ceilings were retained (the thickness of additional shielding must be in a range from 30 mm to 50 mm). The construction could be finished on the agreed date and in the required quality. This solution was acceptable for all participants as the most acceptable solution from the economic point of view.
The State Office for Nuclear Safety, regulatory body, tested in detail the shielding properties during full operation of the linear accelerator. During this stricter inspection, no increase of dose rates outside the shielding walls was observed[3].

4. Conclusions

The radiation density gauges can continuously monitor the critical concrete and/or consolidation work. Their introduction in a wide building practice is necessary and this was manifested by an increase of building quality.
The workers from Brno University of Technology measured the densities of concrete mixtures at the building sites of two nuclear power plants, and recently at 16 building sites of oncological irradiators in hospitals. Based upon our experience, the laboratory quality of concrete is also achieved at raw buildings by using the radiation density gauges.

Acknowledgements

The paper has been prepared by research grant GAČR 103/06/0891 “Testing methods of massive reinforced concrete structures” and CIDEAS (Centre for Integrated DEsign of Advanced Structures) at Faculty of Civil Engineering, Brno University of Technology .

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